

Singlet scalar Dark matter in $U(1)_{B-L}$ models without right-handed neutrinos

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We investigate the phenomenology of a singlet scalar dark matter in a simple $B-L$ gauge extension of the Standard Model where the dark matter particle is charged under the $U(1)_{B-L}$ symmetry. The non-trivial gauge anomalies are canceled with the introduction of three exotic fermions with $B-L$ charges as $-4, -4, 5$, instead of right-handed neutrinos $\nu_{Ri}, i = 1, 2, 3$ with $B-L = -1$ in conventional $U(1)_{B-L}$ model. Without the need of any ad-hoc discrete symmetry, the $B-L$ charge plays a crucial role in stabilizing the dark matter. The dark matter phenomenology is governed mostly by Z' -portal and partly with Higgs portal. The relic abundance is dominated by Z' mediated annihilation channels while the direct detection cross section gets contributions from Z' as well as Higgs mediated processes. We show the allowed parameter space consistent with WMAP data for relic density as well as from direct detection experiments like LUX, XENON100 and XENON1T. Finally we comment on semi-annihilation of dark matter and relic density for particular choice of $B-L$ charge.

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I. INTRODUCTION

Although there are indirect astrophysical evidences for the existence of dark matter contributing with a relic density $\Omega h^2 \simeq 0.12$, about 25% to the energy budget of the Universe [1], still we know only very little about the nature of the dark matter. In particular the unknowns are: what kind of particle it is, i.e., scalar, fermion or vector etc., and to which beyond the Standard Model framework it belongs to (see the recent review article [2] for details). In this respect, models in which the difference between baryon and lepton number ($B - L$) is gauged, are economic extensions of the Standard Model [3–6] (see also few earlier works in this direction [7–10]). One of the interesting aspects is that in its standard form, the presence of right-handed neutrinos and thus the type-I seesaw mechanism for neutrino mass generation appears naturally. In addition, attempts have already been made within this economic extensions of SM where dark matter can be incorporated as well [11–20].

It is widely believed that weakly interacting massive particles (WIMPs) fulfill the necessary criteria of dark matter not too far from the electroweak scale, which provides the opportunity to test them at the current or near future direct or indirect dark matter detection experiments. One of the fundamental questions is how to address the stability of the dark matter. Within the gauged $B - L$ extensions of the Standard Model, the stability of the dark matter can be taken care of by imposing an extra discrete symmetry on top of the gauge symmetry [14–16, 19]. In these class of models one of the right-handed neutrinos introduced for gauge anomaly cancellation is odd under the additional discrete symmetry and acts as a dark matter candidate. Attempts are also made to ensure the stability of the dark matter by choosing the appropriate $B - L$ charge of dark matter [12, 13, 17, 18, 20]. There are other variants of gauged $B - L$ extension of SM, where the additional fermions carry exotic integer value of $B - L$ charge. The discussion of scalar dark matter and neutrino phenomenology have been explored in the recent works [21, 22], while a beautiful connection between dark matter abundance and matter-antimatter asymmetry has been investigated in Ref. [20] within WIMPy Leptogenesis.

In this work, we attempt to study the phenomenology of a scalar dark matter within the context of gauged $B - L$ model without the introduction of any right-handed neutrinos, which are generally present in the conventional $B - L$ theory. The induced gauge anomalies are canceled by assigning appropriate $B - L$ charges to the additional fermions. The key point to note here is that the stability of the scalar singlet dark matter is ensured by the peculiar choice of $B - L$ charges and not by introducing any ad-hoc discrete symmetry.

The plan of the paper is as follows. We discuss in Sec-II, the simplest $B - L$ extension

of SM without right-handed neutrinos along with allowed solutions for gauge anomaly cancellation, vacuum stability and mass spectrum of the scalar sector. In Sec-III, we discuss the scalar singlet dark matter phenomenology in view of relic density and direct detection perspective. We then discuss semi-annihilation of dark matter candidates in Sec-IV followed by conclusion in Sec-V.

II. THE MODEL FRAMEWORK

It is believed that the $B - L$ gauge extension of Standard Model (SM) is the simplest model one can think of from the point of view of a self-consistent gauge theory where the difference between baryon and lepton number is promoted to local gauge symmetry. The gauge group of this simplest $B - L$ model is $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$, omitting the $SU(3)_C$ structure for simplicity. Originally, these models are motivated to cancel the triangle gauge anomalies

$$\mathcal{A}_1 [U(1)_{B-L}^3], \mathcal{A}_2 [(\text{gravity})^2 \times U(1)_{B-L}], \quad (1)$$

with the inclusion of right-handed neutrinos $\nu_{Ri} (i = 1, 2, 3)$ having the $B - L$ charges -1 (the other gauge anomalies shown in Fig. 1 trivially cancel). These right-handed neutrinos can generate light neutrino masses via the type-I seesaw mechanism [23–26] and account for matter-antimatter asymmetry of the universe. However, we present below few other possible solutions to overcome these anomalies.

A. Anomaly cancellation with additional fermions having exotic B-L charges

Anomaly cancellation within the simple $B - L$ gauge extension of the SM can also be done with the introduction of additional neutral fermions $N_{1R}(-4)$, $N_{2R}(-4)$, $N_{3R}(+5)$ [21, 22, 27]. We show here how these non-trivial anomalies are exactly canceled out with the inclusion of additional fermions presented in Table. I and diagrams shown in Fig. 1, with explicit calculation

$$\begin{aligned} \mathcal{A} [U(1)_{B-L}^3] &= \mathcal{A}_1^{\text{SM}} (U(1)_{B-L}^3) + \mathcal{A}_1^{\text{New}} (U(1)_{B-L}^3) = -3 + (4)^3 + (4)^3 + (-5)^3 = 0, \\ \mathcal{A} [\text{gravity}^2 \times U(1)_{B-L}] &\propto \mathcal{A}_1^{\text{SM}} (U(1)_{B-L}) + \mathcal{A}_1^{\text{New}} (U(1)_{B-L}) = -3 + (4) + (4) + (-5) = 0. \end{aligned}$$

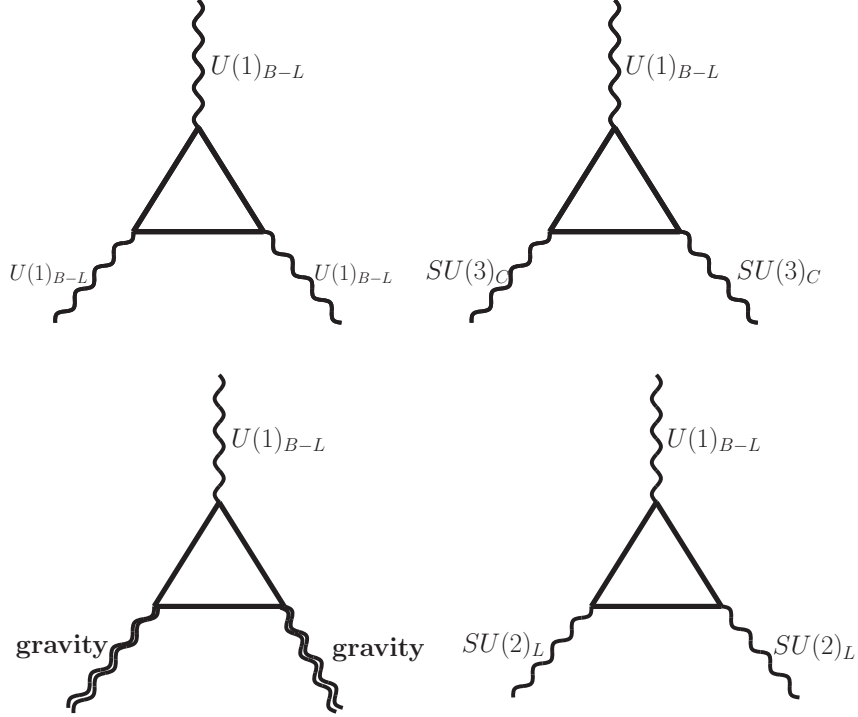


FIG. 1: The one-loop triangle gauge anomalies for the present $B - L$ model

Exotic Fermions	N_{1R}	N_{2R}	N_{3R}
$B - L$	-4	-4	5
$\mathcal{A}_1 (U(1)_{B-L}^3)$	64	64	-125
$\mathcal{A}_4 (\text{gravity}^2 \times U(1)_{B-L})$	4	4	-5

TABLE I: Additional fermions with exotic charges contributing to triangle gauge anomaly.

B. Anomaly cancellation with additional fermions having fractional B-L charges

There can be a different solution to cancel the gauge anomalies, where we require four additional fermions carrying fractional $B - L$ charges (first proposed in Ref. [28]). We present below with explicit calculation for the new gauge anomalies $\mathcal{A}_1 (U(1)_{B-L}^3)$ and $\mathcal{A}_4 (\text{gravity}^2 \times U(1)_{B-L})$ as

$$\begin{aligned}
 \mathcal{A} [U(1)_{B-L}^3] &= \mathcal{A}_1^{\text{SM}} (U(1)_{B-L}^3) + \mathcal{A}_1^{\text{New}} (U(1)_{B-L}^3) \\
 &= -3 + \left(\frac{4}{3}\right)^3 + \left(\frac{1}{3}\right)^3 + \left(\frac{2}{3}\right)^3 + \left(\frac{2}{3}\right)^3 = 0, \\
 \mathcal{A} [\text{gravity}^2 \times U(1)_{B-L}] &\propto \mathcal{A}_1^{\text{SM}} (U(1)_{B-L}) + \mathcal{A}_1^{\text{New}} (U(1)_{B-L}) \\
 &= -3 + \left(\frac{4}{3}\right) + \left(\frac{1}{3}\right) + \left(\frac{2}{3}\right) + \left(\frac{2}{3}\right) = 0.
 \end{aligned}$$

Exotic Fermions	ξ_L	η_L	χ_{1R}	χ_{2R}
$B - L$	4/3	1/3	-2/3	-2/3
$\mathcal{A}_1 (U(1)_{B-L}^3)$	64/27	1/27	8/27	8/27
$\mathcal{A}_4 (\text{gravity}^2 \times U(1)_{B-L})$	4/3	1/3	2/3	2/3

TABLE II: Additional fermions with fractional charges contributing to triangle gauge anomaly.

	Field	$SU(2)_L \times U(1)_Y$	$U(1)_{B-L}$
Fermions	$Q_L \equiv (u, d)_L^T$	$(\mathbf{2}, 1/6)$	1/3
	u_R	$(\mathbf{1}, 2/3)$	1/3
	d_R	$(\mathbf{1}, -1/3)$	1/3
	$\ell_L \equiv (\nu, e)_L^T$	$(\mathbf{2}, -1/2)$	-1
	e_R	$(\mathbf{1}, -1)$	-1
	N_{1R}	$(\mathbf{1}, 0)$	-4
	N_{2R}	$(\mathbf{1}, 0)$	-4
	N_{3R}	$(\mathbf{1}, 0)$	5
Scalars	H	$(\mathbf{2}, 1/2)$	0
	ϕ_{DM}	$(\mathbf{1}, 0)$	n_{DM}
	ϕ_1	$(\mathbf{1}, 0)$	-1
	ϕ_8	$(\mathbf{1}, 0)$	8

TABLE III: Particle spectrum and their charges of the proposed $U(1)_{B-L}$ model.

We consider here an anomaly free model built up based on $U(1)_{B-L}$ extension of the standard model without right-handed neutrinos as already discussed in subsection-IIA. We introduce a scalar dark matter ϕ_{DM} , singlet under the SM gauge group but charged under $U(1)_{B-L}$. We need two more scalar singlets ϕ_1 and ϕ_8 for spontaneous symmetry breaking of $U(1)_{B-L}$ symmetry i.e., $SU(2) \times U(1)_Y \times U(1)_{B-L}$ to $SU(2) \times U(1)_Y$ and to provide Majorana masses for the exotic fermions N_{1R} , N_{2R} and N_{3R} . The particle content of the present model is given in Table.III.

The relevant terms in the Lagrangian for fermions in the present model is given by

$$\begin{aligned}
\mathcal{L}_{\text{Kin.}}^{\text{fermion}} = & \overline{Q}_L i\gamma^\mu \left(\partial_\mu + ig \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu + \frac{1}{6} i g' B_\mu + \frac{1}{3} i g_{\text{BL}} Z'_\mu \right) Q_L \\
& + \overline{u}_R i\gamma^\mu \left(\partial_\mu + \frac{2}{3} i g' B_\mu + \frac{1}{3} i g_{\text{BL}} Z'_\mu \right) u_R \\
& + \overline{d}_R i\gamma^\mu \left(\partial_\mu - \frac{1}{3} i g' B_\mu + \frac{1}{3} i g_{\text{BL}} Z'_\mu \right) d_R \\
& + \overline{\ell}_L i\gamma^\mu \left(\partial_\mu + ig \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - \frac{1}{2} i g' B_\mu - i g_{\text{BL}} Z'_\mu \right) \ell_L \\
& + \overline{e}_R i\gamma^\mu \left(\partial_\mu - i g' B_\mu - i g_{\text{BL}} Z'_\mu \right) e_R \\
& + \overline{N}_{1R} i\gamma^\mu \left(\partial_\mu - 4i g_{\text{BL}} Z'_\mu \right) N_{1R} + \overline{N}_{2R} i\gamma^\mu \left(\partial_\mu - 4i g_{\text{BL}} Z'_\mu \right) N_{2R} \\
& + \overline{N}_{3R} i\gamma^\mu \left(\partial_\mu + 5i g_{\text{BL}} Z'_\mu \right) N_{3R} .
\end{aligned} \tag{2}$$

The relevant interaction Lagrangian for the scalar sector is as follows

$$\begin{aligned}
\mathcal{L}_{\text{scalar}} = & (\mathcal{D}_\mu H)^\dagger (\mathcal{D}^\mu H) + (\mathcal{D}_\mu \phi_{\text{DM}})^\dagger (\mathcal{D}^\mu \phi_{\text{DM}}) + (\mathcal{D}_\mu \phi_1)^\dagger (\mathcal{D}^\mu \phi_1) \\
& + (\mathcal{D}_\mu \phi_8)^\dagger (\mathcal{D}^\mu \phi_8) - V(H, \phi_{\text{DM}}, \phi_1, \phi_8) ,
\end{aligned} \tag{3}$$

where the covariant derivatives are

$$\begin{aligned}
\mathcal{D}_\mu H &= \partial_\mu H + i g \vec{W}_{\mu L} \cdot \frac{\vec{\tau}}{2} H + i \frac{g'}{2} B_\mu H , \\
\mathcal{D}_\mu \phi_{\text{DM}} &= \partial_\mu \phi_{\text{DM}} + i n_{\text{DM}} g_{\text{BL}} Z'_\mu \phi_{\text{DM}} , \\
\mathcal{D}_\mu \phi_1 &= \partial_\mu \phi_1 - i g_{\text{BL}} Z'_\mu \phi_1 , \\
\mathcal{D}_\mu \phi_8 &= \partial_\mu \phi_8 + 8i g_{\text{BL}} Z'_\mu \phi_8 .
\end{aligned} \tag{4}$$

The Yukawa interaction for the present model is given by

$$\begin{aligned}
\mathcal{L}_{\text{Yuk}} = & Y_u \overline{Q}_L \widetilde{H} u_R + Y_d \overline{Q}_L H d_R + Y_e \overline{\ell}_L H e_R + Y_\nu \overline{\ell}_L \widetilde{H} N_R \\
& + \sum_{\alpha=1,2} h_{\alpha 3} \phi_1 \overline{N}_{\alpha R}^c N_{3R} + \sum_{\alpha,\beta=1,2} h_{\alpha\beta} \phi_8 \overline{N}_{\alpha R}^c N_{\beta R} ,
\end{aligned}$$

with $\widetilde{H} = i\sigma_2 H^*$.

C. Scalar Potential Minimization and Stability criteria

The scalar potential of this model is given by

$$\begin{aligned}
V(H, \phi_{\text{DM}}, \phi_1, \phi_8) = & \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_1^2 \phi_1^\dagger \phi_1 + \lambda_1 (\phi_1^\dagger \phi_1)^2 + \mu_8^2 \phi_8^\dagger \phi_8 + \lambda_8 (\phi_8^\dagger \phi_8)^2 \\
& + \mu_{\text{DM}}^2 \phi_{\text{DM}}^\dagger \phi_{\text{DM}} + \lambda_{\text{DM}} (\phi_{\text{DM}}^\dagger \phi_{\text{DM}})^2 + \lambda_{H1} (H^\dagger H) (\phi_1^\dagger \phi_1) + \lambda_{H8} (H^\dagger H) (\phi_8^\dagger \phi_8) \\
& + \lambda_{18} (\phi_1^\dagger \phi_1) (\phi_8^\dagger \phi_8) + \lambda_{HD} (H^\dagger H) (\phi_{\text{DM}}^\dagger \phi_{\text{DM}}) + \lambda_{D1} (\phi_{\text{DM}}^\dagger \phi_{\text{DM}}) (\phi_1^\dagger \phi_1) \\
& + \lambda_{D8} (\phi_{\text{DM}}^\dagger \phi_{\text{DM}}) (\phi_8^\dagger \phi_8) .
\end{aligned} \tag{5}$$

The scalar components of the fields H , ϕ_1 and ϕ_8 can be parametrized in terms of real scalars and pseudo scalars as

$$\begin{aligned} H^0 &= \frac{1}{\sqrt{2}}(v + h) + \frac{i}{\sqrt{2}}A^0, \\ \phi_1^0 &= \frac{1}{\sqrt{2}}(v_1 + h_1) + \frac{i}{\sqrt{2}}A_1, \\ \phi_8^0 &= \frac{1}{\sqrt{2}}(v_8 + h_8) + \frac{i}{\sqrt{2}}A_8, \end{aligned} \quad (6)$$

where $\langle H \rangle = v/\sqrt{2}$, $\langle \phi_1 \rangle = v_1/\sqrt{2}$, and $\langle \phi_8 \rangle = v_8/\sqrt{2}$. The singlet dark matter field denoted by $\phi_{\text{DM}} = \frac{(S+iA)}{\sqrt{2}}$ doesn't acquire any VEV and the masses of real and imaginary components of ϕ_{DM} are given by

$$\begin{aligned} M_{\text{DM}}^2 &= \mu_{\text{DM}}^2 + \frac{\lambda_{HD}}{2}v^2 + \frac{\lambda_{D1}}{2}v_1^2 + \frac{\lambda_{D8}}{2}v_8^2, \\ M_A^2 &= \mu_{\text{DM}}^2 + \frac{\lambda_{HD}}{2}v^2 + \frac{\lambda_{D1}}{2}v_1^2 + \frac{\lambda_{D8}}{2}v_8^2. \end{aligned} \quad (7)$$

The minimization conditions for the scalar potential in eqn. 5 follows as

$$\begin{aligned} \mu_H^2 &= - \left(\lambda_H v^2 + \frac{\lambda_{H1}}{2}v_1^2 + \frac{\lambda_{H8}}{2}v_8^2 \right), \\ \mu_1^2 &= - \left(\lambda_1 v_1^2 + \frac{\lambda_{H1}}{2}v^2 + \frac{\lambda_{18}}{2}v_8^2 \right), \\ \mu_8^2 &= - \left(\lambda_8 v_8^2 + \frac{\lambda_{H8}}{2}v^2 + \frac{\lambda_{18}}{2}v_1^2 \right). \end{aligned} \quad (8)$$

Since Higgs boson h has been discovered at LHC, we consider zero mixing of H with the scalars ϕ_1 and ϕ_8 i.e., the parameters λ_{H1} , λ_{H8} are neglected. The vacuum stability conditions of the scalar potential are given by [29, 30]

$$\Lambda = \begin{pmatrix} \lambda_{\text{DM}} & \lambda_{D1} & \lambda_{D8} \\ \lambda_{D1} & \lambda_1 & \lambda_{18} \\ \lambda_{D8} & \lambda_{18} & \lambda_8 \end{pmatrix}, \quad (9)$$

$$\lambda_H \geq 0, \lambda_{HD} \geq 0, \lambda_{\text{DM}} \geq 0, \lambda_1 \geq 0, \lambda_8 \geq 0,$$

$$\lambda_{D1} + \sqrt{\lambda_{\text{DM}}\lambda_1} \geq 0, \lambda_{D8} + \sqrt{\lambda_{\text{DM}}\lambda_8} \geq 0, \lambda_{18} + \sqrt{\lambda_1\lambda_8} \geq 0,$$

$$\sqrt{\lambda_{\text{DM}}\lambda_1\lambda_8} + \lambda_{D1}\sqrt{\lambda_8} + \lambda_{D8}\sqrt{\lambda_1} + \lambda_{18}\sqrt{\lambda_{\text{DM}}} \geq 0 \text{ provided with } \text{Det}[\Lambda] \geq 0.$$

D. Mixing in the scalar spectrum

Since there is non-zero mixing between the two scalar singlets i.e., $\lambda_{18} \neq 0$, one can write a mass matrix in the (h_1, h_8) basis as

$$\mathcal{M}_0^2 = \begin{pmatrix} \mu_1^2 + 3\lambda_1 v_1^2 + \frac{\lambda_{H1}}{2}v^2 + \frac{\lambda_{18}}{2}v_8^2 & \lambda_{18}v_1v_8 \\ \lambda_{18}v_1v_8 & \mu_8^2 + 3\lambda_8 v_8^2 + \frac{\lambda_{H8}}{2}v^2 + \frac{\lambda_{18}}{2}v_1^2 \end{pmatrix}. \quad (10)$$

Using the minimization conditions 8 we get

$$\mathcal{M}_0^2 = \begin{pmatrix} 2\lambda_1 v_1^2 & \lambda_{18} v_1 v_8 \\ \lambda_{18} v_1 v_8 & 2\lambda_8 v_8^2 \end{pmatrix}. \quad (11)$$

Now we diagonalize the mass matrix (11) as $U^\dagger \mathcal{M}_0^2 U = \mathcal{M}_d^2$, where the rotation matrix U is given as

$$U = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix}. \quad (12)$$

The mixing angle α is derived to be $\tan 2\alpha = \frac{\lambda_{18} v_1 v_8}{(\lambda_8 v_8^2 - \lambda_1 v_1^2)}$ and the obtained mass eigenstates denoted by H_1, H_2 satisfy

$$\begin{aligned} h_1 &= H_1 \cos \alpha + H_2 \sin \alpha, \\ h_8 &= -H_1 \sin \alpha + H_2 \cos \alpha, \end{aligned} \quad (13)$$

Now we study the stability criteria for S to be the potential DM candidate in the following section.

III. SCALAR SINGLET DARK MATTER

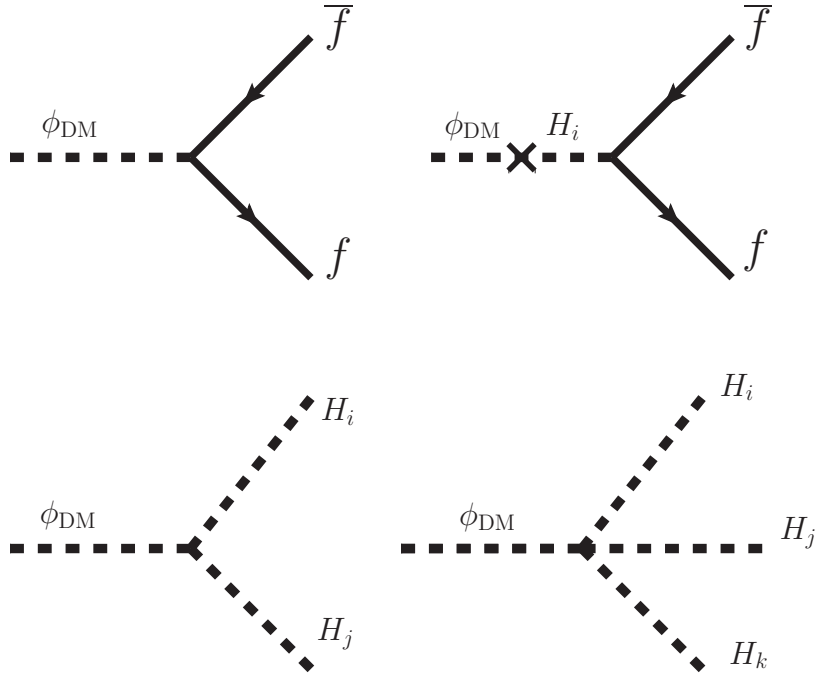


FIG. 2: Feynman diagrams leading to decay of scalar singlet dark matter ϕ_{DM} .

A. Stability of singlet scalar dark matter

Dark matter particle has to be electrically neutral and should be stable over cosmological time scales. With this motivation numerous frameworks were proposed based on an unbroken discrete symmetry [31, 32] forbidding the decay of DM. Furthermore, this discrete symmetry is expected to break at Planck scale and thus induce the decay of DM making it unstable. In the present model, we don't assume any ad-hoc discrete symmetry as such which can stabilize the DM. Rather we choose the $B - L$ charge (say n_{DM}) in such a way that there won't be any decay channel as displayed in Fig. 2 for the DM [33] i.e., ϕ_{DM} . For example, to avoid the cubic term in the scalar potential of the form $\phi_{\text{DM}}H_iH_j$ where H_i, H_j denote the physical masses for any of the scalar H, ϕ_1 and ϕ_8 , the possible values of $n_{\text{DM}} = 0, \pm 2, \pm 7, \pm 9, \pm 16$ are not allowed. Similarly if we don't want term like $\phi_{\text{DM}}H_iH_jH_k$, the value of n_{DM} is restricted to $n_{\text{DM}} \neq \pm 1, \pm 3, \pm 6, \pm 8, \pm 10$. Thus the allowed values of n_{DM} are $\pm 4, \pm 5$ and fractional charges.

B. Relic Abundance

Choosing $n_{\text{DM}} = 4, 5$ one can assure the stability of the scalar singlet ϕ_{DM} and study its phenomenology in the prospects of dark matter observables such as relic abundance and direct detection cross section. Based on the structure of the model built, the DM can have scalar and gauge interactions. During this study we give importance to gauge interactions by assuming the mixing between the DM and scalars is negligible compared to that of with gauge boson Z' . Furthermore, in this analysis we restrict ourselves to the mass regime $M_{\text{DM}} < M_{H_{1,2}} < M_{Z'}$. The relevant interaction term playing a dominant role in relic density observable with Z' being a connector between the visible and dark sector is given by

$$\mathcal{L}_I \supset -n_{\text{DM}}ig_{\text{BL}}Z'_\mu(S\partial^\mu A - A\partial^\mu S) - n_{\text{BL}}^f g_{\text{BL}}\bar{f}\gamma^\mu f Z'_\mu. \quad (14)$$

Here n_{BL}^f denotes the $B - L$ charge for the SM fermion f .

The expression for the corresponding annihilation channel of singlet dark matter S is

$$\hat{\sigma}_{ff} = \sum_f \frac{n_{\text{DM}}^2 (n_{\text{BL}}^f)^2 g_{\text{BL}}^4 c_f}{12\pi s} \frac{(s - 4M_{\text{DM}}^2)(s + 2M_f^2)}{[(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2]} \frac{(s - 4M_f^2)^{\frac{1}{2}}}{(s - 4M_{\text{DM}}^2)^{\frac{1}{2}}}, \quad (15)$$

where c^f denotes the color charge of the fermion f with mass M_f . $M_{Z'}$ is the mass of the heavy gauge boson Z' given by $M_{Z'} = g_{\text{BL}}\sqrt{v_1^2 + 64v_8^2}$ with the decay width $\Gamma_{Z'}$. The relic abundance of dark matter is computed by

$$\Omega h^2 = \frac{2.14 \times 10^9 \text{ GeV}^{-1}}{g_*^{1/2} M_{\text{pl}}} \frac{1}{J(x_f)}, \quad (16)$$

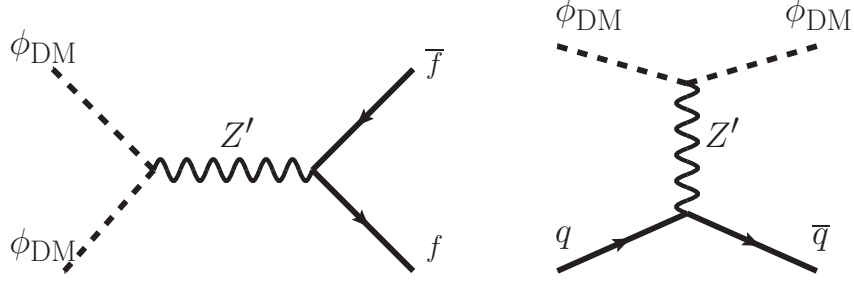


FIG. 3: Feynman diagrams for annihilation channel for $\phi_{\text{DM}}\phi_{\text{DM}}^\dagger \rightarrow f\bar{f}$ via Z' gauge boson shown in left-panel for relic density computation. The right-panel shows the spin-independent dark matter cross section scattered off nuclei.

where $M_{\text{Pl}} = 1.22 \times 10^{19}$ GeV is the Planck mass, $g_* = 106.75$ denoting the total number of effective relativistic degrees of freedom, and $J(x_f)$ reads as

$$J(x_f) = \int_{x_f}^{\infty} \frac{\langle \sigma v \rangle(x)}{x^2} dx. \quad (17)$$

The thermally averaged annihilation cross section $\langle \sigma v \rangle$ is given by

$$\langle \sigma v \rangle(x) = \frac{x}{8M_{\text{DM}}^5 K_2^2(x)} \int_{4M_{\text{DM}}^2}^{\infty} \hat{\sigma} \times (s - 4M_{\text{DM}}^2) \sqrt{s} K_1 \left(\frac{x\sqrt{s}}{M_{\text{DM}}} \right) ds. \quad (18)$$

The functions K_1 , K_2 denote the modified Bessel functions and $x = M_{\text{DM}}/T$, where T is the temperature. The analytical expression for the freeze out parameter x_f is given as

$$x_f = \ln \left(\frac{0.038 g M_{\text{Pl}} M_{\text{DM}} \langle \sigma v \rangle(x_f)}{(g_* x_f)^{1/2}} \right). \quad (19)$$

Here g is the count of number of degrees of freedom of the dark matter particle S .

We have implemented the model in LanHEP [35] to produce the model files required for micrOMEGAs [36–38] package to compute the relic abundance of scalar DM. The only parameters to be analyzed to understand the behavior of relic abundance are the $B - L$ charge of the DM, i.e., n_{DM} , the gauge coupling g_{BL} and the mass of the mediator $M_{Z'}$. We take the constraint from LEP-II bound [34] on the ratio $r_{\text{BL}} = \frac{M_{Z'}}{g_{BL}}$ to be above 6 TeV. Fig. 4 displays the variation of DM abundance Ωh^2 with the singlet DM mass M_{DM} . From the figure one can notice that all the curves were plotted satisfying the LEP-II bound get a resonance at $M_{\text{DM}} = M_{Z'}/2$ and are consistent with current relic constraint from Planck data [1].

For the viable parameter space, we vary r_{BL} in the range 6 – 15 TeV [34], $M_{Z'}$ in the mass region 2 – 5 TeV and M_{DM} in 200 – 2000 GeV range to display in Fig. 5 the correlation plots of various parameters such as $M_{Z'}$ and g_{BL} with the mass of singlet dark matter M_{DM} that effect the relic abundance. From left panel plot it is clear that the relic curve satisfies

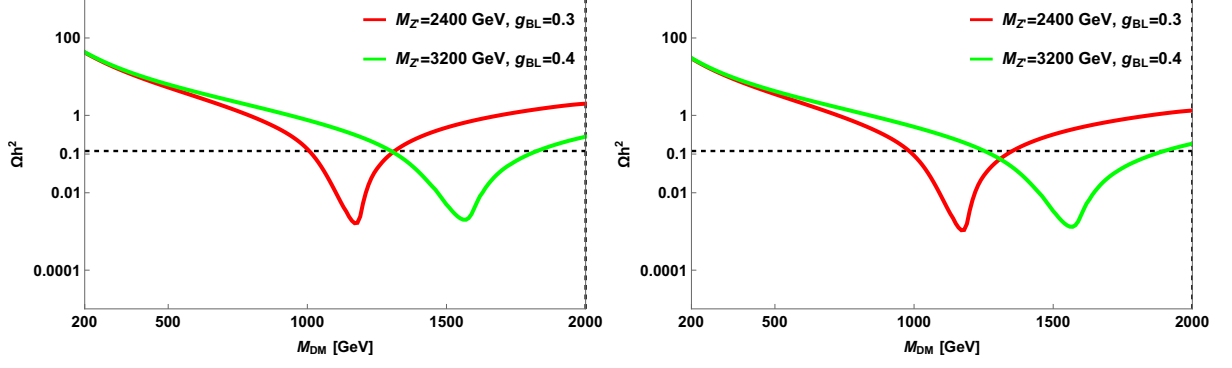


FIG. 4: Variation of relic abundance Ωh^2 with the mass of DM for two different sets of $M_{Z'}$ and g_{BL} values consistent with LEP-II bound [34]. Left panel denotes the variation for $n_{DM} = 4$ and right panel displays the behavior for $n_{DM} = 5$. Here the horizontal line represents the central value of the relic density.

the current relic density [1] on the either side of the resonance i.e., $M_{DM} = M_{Z'}/2$. The plot in the right panel puts a constraint on the allowed range of g_{BL} to be $(0.2 - 0.8)$ which is also consistent with perturbativity [12].

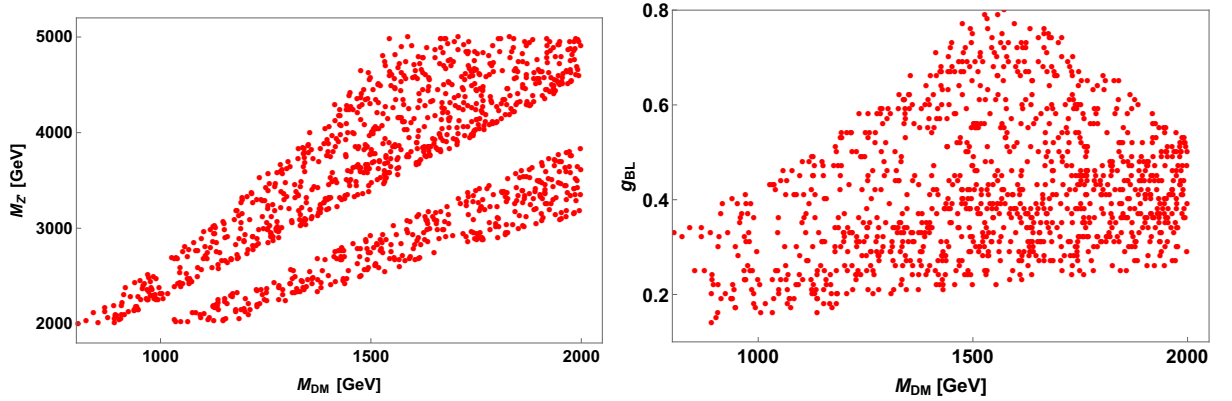


FIG. 5: Correlation plots defining the allowed region of various parameters $M_{Z'}$ and g_{BL} respectively with the mass of dark matter M_{DM} consistent with 3σ range in current relic constraint for $n_{DM} = 4$.

C. Direct searches

Now we look for the constraints on the model parameters due to direct detection limits. In the present case, the spin-independent (SI) direct detection cross-section is found to get contributions from the h -portal and the Z' -portal channels. The interaction terms for

Z' -mediated t-channel processes shown in the right panel of Fig. 3 is given as

$$\mathcal{L} \supset -n_{\text{DM}} i g_{\text{BL}} Z'_\mu (S \partial^\mu A - A \partial^\mu S) - \frac{1}{3} g_{\text{BL}} Z'_\mu \bar{u} \gamma^\mu u - \frac{1}{3} g_{\text{BL}} Z'_\mu \bar{d} \gamma^\mu d. \quad (20)$$

Thus, the effective Lagrangian follows as

$$i\mathcal{L}_{\text{eff}} \supset -\frac{n_{\text{DM}} g_{\text{BL}}^2}{3M_{Z'}^2} (S \partial^\mu A - A \partial^\mu S) \bar{u} \gamma_\mu u - \frac{n_{\text{DM}} g_{\text{BL}}^2}{3M_{Z'}^2} (S \partial^\mu A - A \partial^\mu S) \bar{d} \gamma_\mu d. \quad (21)$$

The DM-nuclei cross-section of the singlet scalar DM mediated by the gauge boson Z' is given by [39–46]

$$\sigma_{SI}^N = \frac{1}{16\pi} \left(\frac{M_N M_{\text{DM}}}{M_N + M_{\text{DM}}} \right)^2 |b_N|^2, \quad (22)$$

where M_N is the nuclei mass and the coefficient b_N is given by

$$b_N = (A - Z)b_n + Zb_p, \quad b_n = b_u + 2b_d, \quad b_p = 2b_u + b_d, \quad (23)$$

Here Z and A denote the atomic and the mass number respectively. The parameters b_u and b_d of the effective Lagrangian are defined as

$$\mathcal{L}_{\text{eff}} = b_q X^\mu \bar{q} \gamma^\mu q, \quad \text{where } q = (u, d). \quad (24)$$

In the present model, X^μ takes the form of the vector current given by $X^\mu \simeq iS \partial^\mu A - iA \partial^\mu S$.

Thus, one can find the value of $b_{p,n}$ as

$$b_p = b_n = i \frac{n_{\text{DM}} g_{\text{BL}}^2}{M_{Z'}^2}.$$

Therefore, b_N can have the value

$$b_N = iA \frac{n_{\text{DM}} g_{\text{BL}}^2}{M_{Z'}^2}.$$

Thus, the DM-nuclei SI contribution is given by

$$\sigma_{SI}^N = \frac{1}{16\pi} \left(\frac{M_N M_{\text{DM}}}{M_N + M_{\text{DM}}} \right)^2 |A|^2 \frac{n_{\text{DM}}^2 g_{\text{BL}}^4}{M_{Z'}^4}.$$

For single nucleon, the above expression becomes

$$\sigma_{Z'} = \frac{\mu^2}{16\pi} \frac{n_{\text{DM}}^2 g_{\text{BL}}^4}{M_{Z'}^4}. \quad (25)$$

where $\mu = \left(\frac{M_n M_{\text{DM}}}{M_n + M_{\text{DM}}} \right)$ is the reduced mass of DM-nucleon with M_n being the nucleon mass.

Moving to h -portal SI contribution, the effective Lagrangian is given as

$$\mathcal{L}_{\text{eff}} = \left(\frac{m_q}{v} \right) (\lambda_{HD} v) \frac{1}{m_h^2} S S \bar{q} q, \quad q = (u, d). \quad (26)$$

The h -portal DM-nucleon SI contribution is given by [42, 47–49]

$$\sigma_h = \frac{\lambda_{HD}^2 f_n^2 \mu^2}{\pi} \frac{M_n^2}{M_{\text{DM}}^2 M_h^4}. \quad (27)$$

where $f_n = 0.3 \pm 0.03$ [47]. Therefore, the total contribution to SI DM-nucleon cross-section is given as

$$\sigma_{SI} = \sigma_{Z'} + \sigma_h. \quad (28)$$

The h -portal contribution is dependent on mass of dark matter M_{DM} while Z' -portal contribution is insensitive to it. It is convenient to write the individual contributions (in cm^2) as

$$\sigma_{Z'} = 7.75 \times 10^{-42} \left(\frac{\mu}{1 \text{ GeV}} \right)^2 \times n_{\text{DM}}^2 \times \left(\frac{1 \text{ TeV}}{r_{\text{BL}}} \right)^4, \quad (29)$$

$$\sigma_h = 4.577 \times 10^{-44} \left(\frac{\mu}{1 \text{ GeV}} \right)^2 \times \lambda_{HD}^2 \times \left(\frac{M_n}{1 \text{ GeV}} \right)^2 \times \left(\frac{1 \text{ TeV}}{M_{\text{DM}}} \right)^2. \quad (30)$$

Fig. 6 show the scattered plots describing the Z' -mediated (in the left panel) and the h -mediated (in the right panel) contributions to direct detection cross section. From the plots one can quote that the model is consistent with the limits given by various dark matter direct detection experiments such as LUX [50], XENON100 [51] and XENON1T [52].

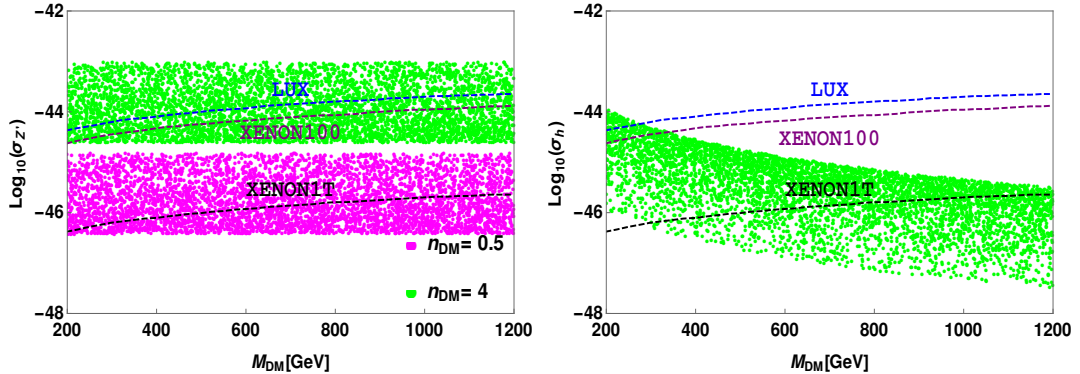


FIG. 6: Spin independent cross section from DM scattering off nucleons versus the mass of the DM with the ratio $r_{\text{BL}} = \frac{M_{Z'}}{g_{\text{BL}}}$ value varied in the range 6 – 15 TeV. The current experimental limits from LUX, XENON100, XENON1T are shown in dashed lines. The left panel depicts the Z' -mediated cross section and right panel shows the contribution from h -mediated channels with the coupling λ_{HD} varied in the range $0.01 \rightarrow 0.1$.

IV. SEMI-ANNIHILATIONS FOR SCALAR DARK MATTER

We have already discussed in the previous section about the relic abundance and direct detection of singlet scalar dark matter within gauged $B - L$ model in the absence

of right-handed neutrinos for possible allowed values of n_{DM} . Here we wish to discuss semi-annihilation of dark matter particles for particular choice of n_{DM} (see Refs.[12, 53] for details). For instance, when $n_{\text{DM}} = 1/3$ there is a quartic term in the Lagrangian of the form

$$\mathcal{L}_{1/3} = \frac{\lambda'_{\text{DM}}}{3} \phi_{\text{DM}}^3 \phi_1 + \text{h.c.} \quad (31)$$

With this interaction term, there is a semi-annihilation channel for scalar dark matter via the process $\phi_{\text{DM}}\phi_{\text{DM}} \rightarrow \phi_{\text{DM}}H_1$ as displayed in Fig. 7.

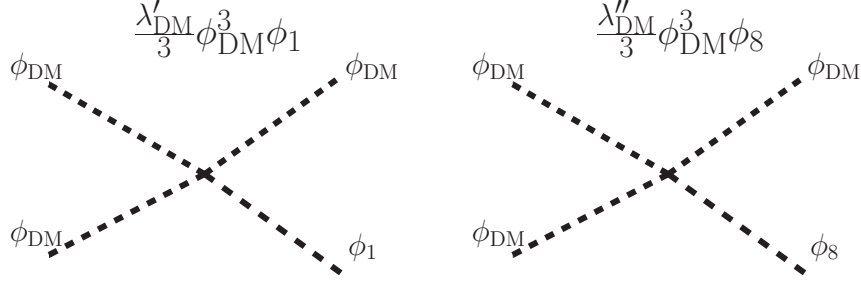


FIG. 7: Feynman diagram for semi-annihilation channel for $\phi_{\text{DM}}\phi_{\text{DM}} \rightarrow \phi_{\text{DM}}\phi_1$ (left-figure) and $\phi_{\text{DM}}\phi_{\text{DM}} \rightarrow \phi_{\text{DM}}\phi_8$ (right-figure).

For simplicity, we assume that the semi-annihilation channel for scalar dark matter is the dominant one while all other interactions of dark matter are irrelevant. Then the cross section for semi-annihilation process $\phi_{\text{DM}}\phi_{\text{DM}} \rightarrow \phi_{\text{DM}}H_1$ is given by

$$\hat{\sigma}_{1/3} = \frac{\lambda'_{\text{DM}}{}^2}{64\pi s} \frac{[(s - (M_{\text{DM}} + M_{H_1})^2)(s - (M_{\text{DM}} - M_{H_1})^2)]^{\frac{1}{2}}}{[s(s - 4M_{\text{DM}}^2)]^{\frac{1}{2}}}. \quad (32)$$

We display in the left panel of Fig. 8 the variation of the relic abundance Ωh^2 with the scalar dark matter mass M_{DM} for various values of the quartic coupling λ'_{DM} values. This scenario is very appealing as the dark matter phenomenology is determined by three free parameters i.e, λ'_{DM} , M_{DM} , M_{H_1} . We fix the mass of scalar mass H_1 to be $M_{H_1} = 200$ GeV. For this choice, we get the simple behavior $\langle\sigma v\rangle \propto \lambda'_{\text{DM}}{}^2/M_{\text{DM}}^2$.

Similarly for $n_{\text{DM}} = 8/3$, the relevant quartic term for semi-annihilation of scalar dark matter particles is given by

$$\mathcal{L}_{8/3} = \frac{\lambda''_{\text{DM}}}{3} \phi_{\text{DM}}^3 \phi_8 + \text{h.c.} \quad (33)$$

And the corresponding cross section for the semi-annihilation process $\phi_{\text{DM}}\phi_{\text{DM}} \rightarrow \phi_{\text{DM}}H_2$ follows as

$$\hat{\sigma}_{8/3} = \frac{\lambda''_{\text{DM}}{}^2}{64\pi s} \frac{[(s - (M_{\text{DM}} + M_{H_2})^2)(s - (M_{\text{DM}} - M_{H_2})^2)]^{\frac{1}{2}}}{[s(s - 4M_{\text{DM}}^2)]^{\frac{1}{2}}}. \quad (34)$$

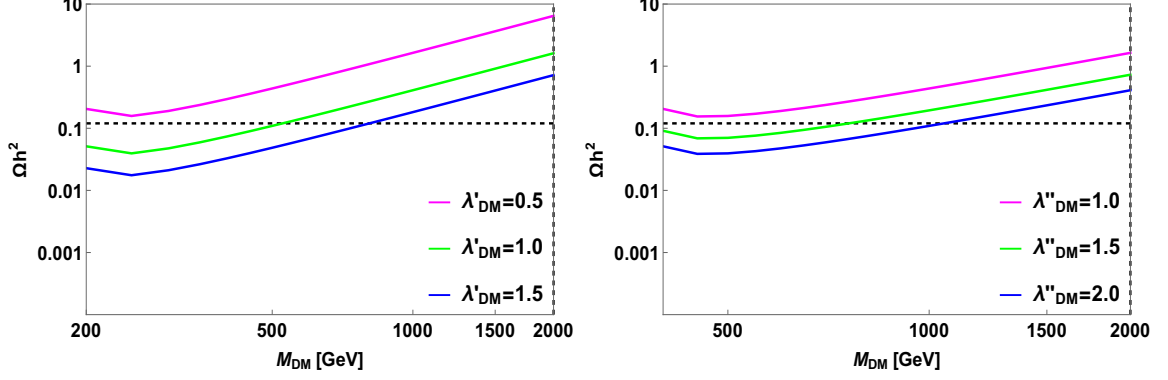


FIG. 8: Variation of relic abundance Ωh^2 with the mass of DM for three different sets of quartic couplings of semi-annihilation term i.e., λ'_{DM} and λ''_{DM} . Left panel denotes the behavior of semi-annihilation term $\phi_{\text{DM}}^3 \phi_1$ and the right panel depicts the impact of semi-annihilation term $\phi_{\text{DM}}^3 \phi_8$ to the relic abundance. Here the horizontal line represents the central value of the relic density.

We repeat the similar procedure as above by fixing $M_{H_2} = 400$ GeV. We show in Fig. 8 (right panel) the dependence of the relic abundance Ωh^2 with the scalar dark matter mass M_{DM} for various values of the quartic coupling λ''_{DM} .

V. CONCLUSION

In this article, we have presented in detail the scalar dark matter phenomenology in the context of an anomaly free $U(1)_{B-L}$ extension of SM. A possible solution to cancel out the resulting non-trivial triangle anomalies of the gauge extension, three heavy neutral fermions $N_{iR} (i = 1, 2, 3)$ with $B - L$ charges $-4, -4$ and $+5$ are added to the existing lepton content of the standard model. Furthermore, the scalar sector is enriched with two scalar singlets ϕ_1 and ϕ_8 to spontaneously break the $U(1)_{B-L}$ gauge symmetry and also to provide the Majorana mass terms for the newly added fermions N_{1R}, N_{2R}, N_{3R} . A scalar singlet ϕ_{DM} is introduced such that the $U(1)_{B-L}$ symmetry takes the burden to forbid its decay making it a stable dark matter candidate. This remarkable gauge extension is economical and rich in dark matter phenomenology. A heavy gauge boson Z' , a resultant of having $U(1)_{B-L}$ as local gauge symmetry acts as mediator between the visible and dark sector.

We have studied the scalar spectrum emphasizing the minimization conditions, vacuum stability and their acquired masses after spontaneous symmetry breaking of $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ gauge symmetry. Choosing a particular $B - L$ charge that can stabilize ϕ_{DM} , we have investigated thoroughly the relic abundance of scalar singlet dark matter with

the major contribution coming from the Z' mediated annihilation channels. Then we have shown the spin-independent direct detection limits on the model parameters consistent with LUX, XENON100 and XENON1T bounds, where the possible channels are of Higgs and Z' mediated. Finally we have commented on semi-annihilations of dark matter to the relic density for a choice of fractional $B - L$ charge for the scalar dark matter. The explored model is quite consistent with current bounds of recent and ongoing dark matter experiments and a testable framework built based on the well-tested local gauge principles of standard model.

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